Constraints and potentials of future irrigation water availability on agricultural production under climate change

Joshua Elliott[a,b,c,1], Delphine Deryng[d], Christoph Müller[e], Katja Frieler[e], Markus Konzmann[e], Dieter Gerten[e], Michael Glotter[f], Martina Flörke[g], Yoshihide Wada[h], Neil Best[a], Stephanie Eisner[g], Balázs M. Fekete[i], Christian Folberth[j], Ian Foster[a,b], Simon N. Gosling[k], Ingjerd Haddeland[l], Nikolay Khabarov[m], Fulco Ludwig[n], Yoshimitsu Masaki[o], Stefan Olin[p], Cynthia Rosenzweig[c,q], Alex C. Ruane[c,q], Yusuke Satoh[r], Erwin Schmid[s], Tobias Stacke[t], Qiuhong Tang[u], and Dominik Wisser[v]

[a]University of Chicago Computation Institute, Chicago, IL 60637; [b]Math and Computer Science Division, Argonne National Laboratory, Lemont, IL 60439; [c]Columbia University Center for Climate Systems Research, New York, NY 10025; [d]Tyndall Center for Climate Change Research, University of East Anglia, Norwich NR4 7TJ, United Kingdom; [e]Potsdam Institute for Climate Impact Research, 14473 Potsdam, Germany; [f]Department of the Geophysical Sciences, University of Chicago, Chicago, IL 60637; [g]Center for Environmental Systems Research, University of Kassel, 34109 Kassel, Germany; [h]Department of Physical Geography, Utrecht University, 3584 CS, Utrecht, The Netherlands; [i]The City College of New York, New York, NY 10031; [j]Swiss Federal Institute of Aquatic Science and Technology, 8600 Dübendorf, Switzerland; [k]University of Nottingham, Nottingham NG7 2RD, United Kingdom; [l]Norwegian Water Resources and Energy Directorate, N-0301 Oslo, Norway; [m]Ecosystems Services and Management Program (ESM), International Institute for Applied Systems Analysis (IIASA), 2361 Laxenburg, Austria; [n]Wageningen University and Research Centre, 6708 PB, Wageningen, The Netherlands; [o]National Institute for Environmental Studies, Tsukuba 305-8506, Japan; [p]Lund University, 223 62 Lund, Sweden; [q]National Aeronautics and Space Administration Goddard Institute for Space Studies, New York, NY 10025; [r]University of Tokyo, Tokyo 153-8505, Japan; [s]University of Natural Resources and Life Sciences, 1180 Vienna, Austria; [t]Max Planck Institute for Meteorology, 20146 Hamburg, Germany; [u]Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China; and [v]Center for Development Research, University of Bonn, 53113 Bonn, Germany

Edited by Hans Joachim Schellnhuber, Potsdam Institute for Climate Impact Research, Potsdam, Germany, and accepted by the Editorial Board October 4, 2013 (received for review January 31, 2013)

We compare ensembles of water supply and demand projections from 10 global hydrological models and six global gridded crop models. These are produced as part of the Inter-Sectoral Impacts Model Intercomparison Project, with coordination from the Agricultural Model Intercomparison and Improvement Project, and driven by outputs of general circulation models run under representative concentration pathway 8.5 as part of the Fifth Coupled Model Intercomparison Project. Models project that direct climate impacts to maize, soybean, wheat, and rice involve losses of 400–1,400 Pcal (8–24% of present-day total) when CO_2 fertilization effects are accounted for or 1,400–2,600 Pcal (24–43%) otherwise. Freshwater limitations in some irrigated regions (western United States; China; and West, South, and Central Asia) could necessitate the reversion of 20–60 Mha of cropland from irrigated to rainfed management by end-of-century, and a further loss of 600–2,900 Pcal of food production. In other regions (northern/eastern United States, parts of South America, much of Europe, and South East Asia) surplus water supply could in principle support a net increase in irrigation, although substantial investments in irrigation infrastructure would be required.

adaptation | agriculture | hydrology | uncertainty

A lack of available water for agricultural production, energy projects, other forms of anthropogenic water consumption, and ecological use is already a major issue in many parts of the world and is expected to grow all of the more severe with increasing population, higher food (especially meat) demand, increasing temperatures, and changing precipitation patterns. Although population growth is generally expected to slow in the coming decades, median forecasts typically assume that the world population will grow close to another 50% above the recent milestone of 7 billion people (1). Compounding population growth are major changes to diet as rapid economic growth in much of the developing world leads to increased wealth and demand for more processed food and animal proteins in consumer diets (2, 3). At the same time that demand for food and animal feed is increasing at a historic pace, countries are also increasingly turning to agricultural commodities as a solution to high fuel prices, energy security, and growing carbon dioxide (CO_2) emissions. Population growth adds further stress by taking land out of agriculture for urban development. For example, between 1982 and 2007, about 9.3 Mha of US agricultural land were converted for development (about 1 ha every 2 min) (4). As the availability of land for agricultural uses continues to stagnate or even decline, focus has shifted to increased land-use intensification and improved management to increase yields on existing lands to meet demand challenges and moderate some fraction of the negative impact of climate change (5–7).

Irrigation is of paramount importance to increasing productivity on existing agricultural lands, and projected per-hectare irrigation consumption is thus an important output of global gridded crop models (GGCMs). Irrigation is also by far the largest component of anthropogenic demand for fresh water and as

Significance

Freshwater availability is relevant to almost all socioeconomic and environmental impacts of climate and demographic change and their implications for sustainability. We compare ensembles of water supply and demand projections driven by ensemble output from five global climate models. Our results suggest reasons for concern. Direct climate impacts to maize, soybean, wheat, and rice involve losses of 400–2,600 Pcal (8–43% of present-day total). Freshwater limitations in some heavily irrigated regions could necessitate reversion of 20–60 Mha of cropland from irrigated to rainfed management, and a further loss of 600–2,900 Pcal. Freshwater abundance in other regions could help ameliorate these losses, but substantial investment in infrastructure would be required.

Author contributions: J.E., K.F., D.G., C.R., and A.C.R. designed research; J.E., D.D., C.M., M.K., D.G., M.G., M.F., Y.W., N.B., S.E., B.M.F., C.F., S.N.G., I.H., N.K., F.L., Y.M., S.O., Y.S., E.S., T.S., Q.T., and D.W. performed research; J.E., D.D., C.M., D.G., M.F., Y.W., S.E., C.F., S.N.G., I.H., N.K., F.L., Y.M., S.O., Y.S., E.S., T.S., and Q.T. contributed new analytic tools; J.E., K.F., and M.K. analyzed data; and J.E., D.D., C.M., and I.F. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Data deposition: The data reported in this paper associated with the Inter-Sectoral Impact Model Intercomparison Project is hosted at http://esg.pik-potsdam.de.

[1]To whom correspondence should be addressed. E-mail: jelliott@ci.uchicago.edu.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1222474110/-/DCSupplemental.

such constitutes an essential part of the global hydrological cycle and thus of global hydrological model (GHM) simulations [Haddeland et al. (8), in this issue of PNAS]. Projected potential irrigation water consumption by crops and managed grasses (henceforth "PIrrUse") is thus a rare overlap among typical GHM and GGCM outputs. The coordinated multisector, multimodel ensembles created in the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) hence allow for not only comparison among distinct models within their respective sectors, but also for a direct comparison between GHMs and GGCMs. Several studies have evaluated the potential impacts of future climate change on irrigation water requirements (9, 10) and the extent to which irrigation may aid adaptation to adverse climatic change effects (5, 6). However, these studies were constrained to a single GHM or GGCM only.

The objectives of the present analysis are to (*i*) compare projections of PIrrUse between GHMs and GGCMs—with and without the effects on plants of increasing atmospheric CO_2 ([CO_2])—and (*ii*) estimate an upper bound for the future availability of renewable fresh water for irrigation using combined projections of water supply from 10 GHMs (11–20) and irrigation water demand (IWD) from both GHMs and 6 GGCMs (11, 21–26) run as part of the Agricultural Model Intercomparison and Improvement Project [AgMIP (27)] and ISI-MIP [see *SI Appendix*, Tables S1–S5 for a summary of participating models and institutional contacts; see also Schewe et al. (28) in this issue of PNAS for a description of the GHMs and simulations and Rosenzweig et al. (29) also in this issue of PNAS for a detailed description of the GGCMs and simulations] to (*iii*) evaluate the potential impacts of (limited) irrigation water availability on future crop productivity and (*iv*) characterize the uncertainty in projections of global potential for irrigation-based adaptation by analyzing a consistent cross-sectoral ensemble of 5 GCMs × 10 GHMs × 6 GGCMs. We identify geographic regions in which a combination of decreased water availability and/or increased demand may reduce water available for irrigation and thus further impact agricultural production beyond what is otherwise expected from climate change, as well as regions with potential for climate change adaptation via intensified irrigation.

Results and Discussion

Irrigation Water Consumption in GHMs and GGCMs. Global PIrrUse on cropland currently equipped for irrigation (30) is projected to evolve in the future with climate change (Fig. 1). We find notable differences between projections of PIrrUse obtained from GGCMs and GHMs that could have a material effect on our assessment of irrigation's potential contribution to future yield growth and climate adaptation. Without the effects of increasing [CO_2], GGCMs generally estimate flat or increasing consumption for PIrrUse on present irrigated area, but the trend is far less than the strong positive trend seen in GHMs. When the effects of increasing [CO_2] are included in GGCMs, these models project a decrease in global irrigation consumption on presently irrigated area from 8% to 15% by end of century, similar to results found for an ensemble of GCMs by Konzmann et al. (10) based on a single model (LPJmL; highlighted in Fig. 1 for the present scenarios). With the exception of LPJmL (Lund-Potsdam-Jena Managed Land Dynamic Global Vegetation and Water Balance Model), which is a GHM that includes detailed dynamic representations of plant and crop processes, the hydrological models did not consider the effects of increasing [CO_2] on plants. As all models are driven by the same climate scenario data, this conflicting behavior between model types must stem from different representations of agricultural land and agrohydrological processes in GHMs and GGCMs.

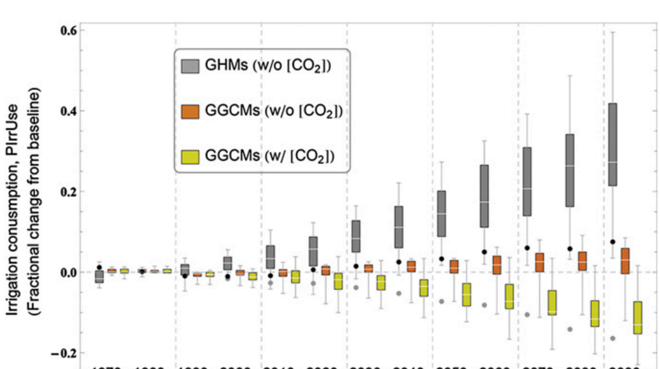

Fig. 1. Comparison of fractional change relative to the model specific average 1980–2010 baseline of projections of total global PIrrUse in RCP 8.5 from all GCM × GHM combination and all GCM × GGCM combination with and without the effects of increasing [CO_2]. Results from LPJmL (mean over all GCMs) with (gray dots) and without (black dots) increasing [CO_2] are shown explicitly. LPJmL is unique in that it falls into both GHM and GGCM categories and is unique among the GHMs in that it provides estimates for PIrrUse both with and without the effects of increasing [CO_2].

Each GHM and GGCM uses an individual mix of explicitly represented land use types. Projections of global total PIrrUse for individual GGCMs combine results for crops not explicitly represented (*SI Appendix*, Fig. S1). All GGCMs considered here simulate dynamic phenology, which accelerates growing seasons in response to warmer climates if there is no adjustment in management (i.e., static sowing dates and varieties). The shortening of the period for which irrigation water is needed can decrease projected consumption. Dynamic phenology is implemented in some GHMs (e.g., LPJmL and H08) and indeed substantial differences in the representations of agricultural land and plant types explain part of the broad range of trends in GHM projections of PIrrUse (*SI Appendix*, Fig. S2). See Haddeland et al. (8) in this issue of PNAS for a more detailed description of GHM representations of agricultural land and irrigation.

Reduced PirrUse from shortened cropping cycles in GGCMs is compounded by the effects of increasing [CO_2] on water use efficiency. These two mechanisms partially counteract or even reverse increasing potential evapotranspiration and temporal and spatial declines in precipitation. The latter effects are the dominant drivers in irrigation water consumption projections of models with static cropping period assumptions.

GHM and GGCM projections of irrigation water consumption are both the results of simplified representations of the complexity of existent irrigation systems. GGCMs here represent only single-cycle cropping systems with simple parameterizations of irrigation events (*SI Appendix*, Tables S3 and S4), whereas regions with irrigation agriculture often cultivate multiple cropping cycles within a year, especially at low latitudes where no seasons are threatened by frost. Similarly, farmers are likely to adapt to the acceleration of maturation in single-cycle systems by using slower maturing varieties. This effect, along with other adaptation strategies, was excluded in the GGCM model setup here for most model runs, as it complicates the analysis and attribution of climate change impacts. GHMs on the other hand generally ignore the effects of increasing [CO_2] on crop water use efficiency, and those with static cropping seasons likely overestimate the increase in irrigation water consumption, especially in regions with strong seasonality in temperature (31).

The differences in crop-specific irrigation water consumption as simulated by the GGCMs highlight the importance of a more complex representation of agricultural dynamics and crop types. For example, in some GHMs that include representations of a limited set of crop types (e.g., LPJmL), crops not explicitly represented are assumed to behave like perennial grasses with regard to transpiration and irrigation consumption. Given extreme differences in the projected trend of PIrrUse for grasses and most annual crops (*SI Appendix*, Fig. S1, especially cotton and sugarcane), approximating row crops with perennial grasses can lead to substantive differences in the overall global trend of irrigation.

Water Withdrawals and Availability. We analyze the balance of irrigation water supply and demand at the level of food production units [FPUs, composites of river basins and economic regions following Cai and Rosegrant (32) with modifications by Kummu et al. (33); *SI Appendix*, Fig. S3]. We estimate potential irrigation water withdrawal or demand (PIrrWW) from PIrrUse based on average current irrigation project efficiencies from Rost et al. (34) and assume that freshwater is freely distributable within FPUs without substantial transportation costs. These large-scale assumptions average significant spatial variability in infrastructure availability (35) and water policy (36) at the local level which may substantially reduce the amount of water available (especially for new irrigation projects) in practice. For these reasons we consider the resulting estimates of water availability for irrigation as upper bounds in most FPUs. We account for environmental flow requirements and the limits from seasonal distribution by assuming an upper availability of 40% of total annual blue water supply (*SI Appendix*, Figs. S4 and S5) and subtract water consumption for other sectors as projected by The WaterGAP model (Water – A Global Assessment and Prognosis) [*SI Appendix*, Fig. S5 and Flörke et al. (37)] from the available water, assuming that irrigation water always has the lowest priority of all water consumers (which is almost always the case).

Irrigation Potential and Constraints. If PIrrWW in a currently irrigated area is projected to be greater than or equal to the projected available renewable water, the agricultural production in that FPU is irrigation constrained (denoted by red in Fig. 2). If projected PIrrWW is less than the projected available renewable water, the FPU has an irrigation adaptation potential equal to the difference (green in Fig. 2). As the major uncertainty of these FPU-balances lies in the different assessment of IWD in GHMs and GGCMs, we consider two distinct scenarios for this input: (*i*) the median of all GCM × GHM combinations (IWDhydro; set represented by gray bars in Fig. 1) and (*ii*) the median of all GCM × GGCM combinations (IWDcrop; set represented by yellow bars in Fig. 1). Fig. 2 summarizes the spatial patterns of water availability/deficiency for these two scenarios at the FPU level. In general, ensemble elements within the IWDhydro scenario show higher baseline irrigation demand in most FPUs, less water available for the expansion of irrigation, and more FPUs requiring contraction of irrigated areas with especially notable differences across the western United States, Mexico, and much of Asia. Even though estimates of total projected irrigation consumption differ substantially in an absolute sense between the crop and water models, the spatial patterns of consumption are similar (*SI Appendix*, Figs. S6 and S7).

Agricultural Potential with Irrigation and Climate Adaptation. We used the GGCM simulations to derive the possible future yield increase due to conversion of rainfed cropland to irrigated cropland in FPUs with irrigation adaptation potential, and, similarly, the possible future yield decrease due to conversion of irrigated cropland to rainfed in FPUs that are projected to be irrigation constrained. The magnitude of these effects is determined by the level of water limitations in rainfed agriculture (sustained only by green water, i.e., on-field precipitation and soil moisture). Consequently, semiarid regions where crops are currently cultivated under rainfed conditions typically show the greatest yield increase under irrigation (Fig. 3). It is apparent by comparison with Fig. 2 that many regions with the largest potential for yield increases from increased irrigation are also those most likely to have binding constraints on water availability. For maximum consistency with the assumptions of the GHMs and GGCMs used to construct the two scenarios of irrigation water availability/deficiency in Fig. 2, we combine irrigation scenario IWDhydro with the climate impacts and per-hectare irrigation-based yield improvements without the effects of increasing [CO_2] and scenario IWDcrop with the production factors with increasing [CO_2]. These choices also lead to scenarios that better span the space of possible future trajectories of climate impacts and irrigation-based adaptation, as the more optimistic/pessimistic water availability scenario (IWDcrop/IWDhydro) is combined with the more optimistic/pessimistic climate impact scenario (with/without the projected beneficial effects of increasing [CO_2]). Irrigation-based yield improvement factors for scenarios without the effects of increasing [CO_2] are very similar to those in Fig. 3.

When assuming maximum conversion of rainfed cropland to irrigated cropland in FPUs with irrigation adaptation potential and reduced irrigation water use in irrigation constrained FPUs (Fig. 2), total caloric production of maize, soybean, wheat, and rice is changed regionally (Fig. 4) according to the projected yield increases under irrigation in Fig. 3. The two scenarios (IWDhydro and IWDcrop) are similar, although differences in the western breadbasket of the United States (most notably the Missouri River Basin) and throughout much of China are significant.

Global Adaptation Potential and Uncertainties. Aggregated globally, expansion of irrigation agriculture has the potential to increase production on current cropland. However, model projections indicate that even under the most optimistic assumptions about freshwater distribution and transportation within FPUs, the beneficial effect would be exhausted by detrimental climate change effects on crop yields by 2070 at the latest, for irrigation scenario IWDcrop and crop yields estimated with the inclusion of the effects of increasing [CO_2] (Fig. 5). By 2090, 57% of the median 730-Pcal reduction due to climate change with effects of increasing [CO_2] could be ameliorated by the net expansion of irrigation according to the more optimistic irrigation scenario (IWDcrop). Under the more pessimistic irrigation scenario (IWDhydro), the limitations on irrigation water supply availability further constrain the potential ameliorating effect of expanded irrigation to only 12% of the 1,840-Pcal reduction in 2090 due to climate change without effects of increasing [CO_2], highlighting the need to improve agricultural productivity by other means. This general mechanism is valid for all GCM × (GGCM or GHM) combinations, although there is considerable variation among the projections of individual ensemble members (Fig. 5).

Our analysis is subject to considerable uncertainties which we address in part here. Agricultural PIrrUse and corresponding increases in productivity have been simulated by the GGCMs

Fig. 2. Median potential end-of-century renewable water abundance/deficiency in average cubic kilometers per year under RCP 8.5 for (*Left*) all GCM × GHM combinations (IWDhydro scenario) for both supply and demand and (*Right*) using all GCM × GGCM combinations for irrigation demands (IWDcrop scenario). Positive values indicate areas with irrigation adaptation potential and negative values indicate irrigation constrained areas. Dark green FPUs are saturated at 50 km^3/y.

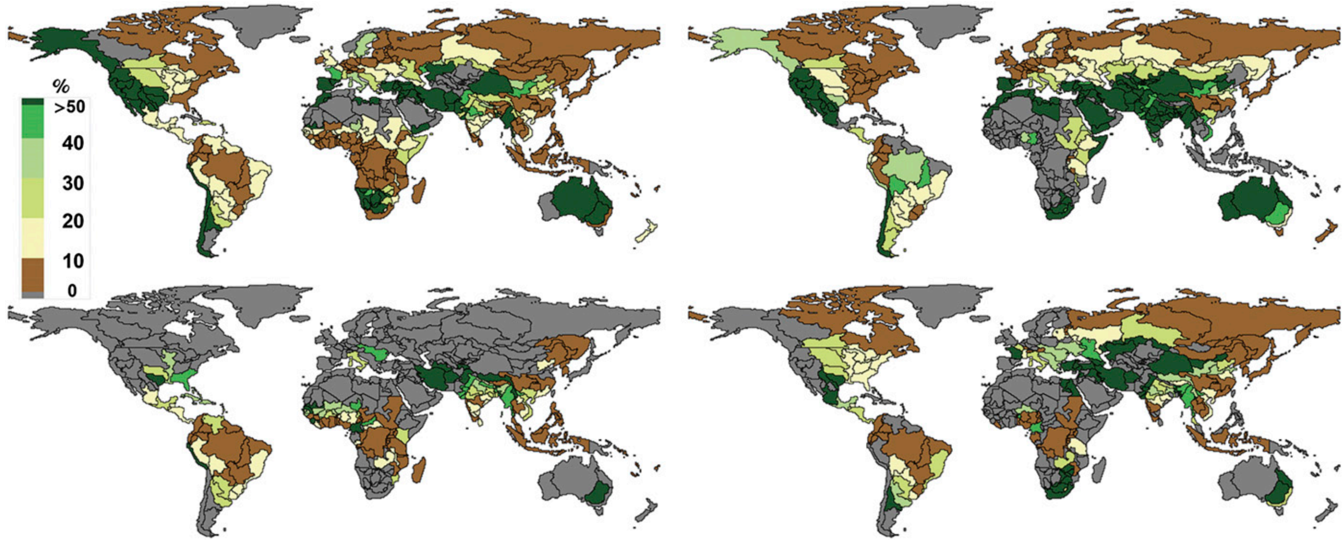

Fig. 3. Median potential per hectare increase in maize (*Upper Left*), wheat (*Upper Right*), soybean (*Lower Right*), and rice (*Lower Left*) yields at the end-of-century from irrigation applied on what are currently rainfed areas for scenarios with the effects of increasing atmospheric CO_2 concentrations included. Maps show median values across all 30 GCM × GGCM combinations in the ensemble for RCP 8.5.

only for irrigation management with a 100% saturation threshold for applications (i.e., once an irrigation event is triggered, water is applied until soil moisture is optimal; *SI Appendix*, Tables S3 and S4). Because the efficiency of irrigation water use (yield per unit water) declines at higher irrigation levels (38), water sharing and deficit irrigation could have an overall beneficial effect in constrained regions. Another source of uncertainty relates to our assumptions regarding fossil groundwater availability. Our results indicate that many regions with high shares of irrigated agriculture are likely to be constrained by future freshwater availability. Because we are concerned with the long-term sustainable supply of freshwater, we assume no water supply from fossil groundwater. This is consistent in some areas with the observed depletion of (fossil) groundwater reserves (e.g., ref. 39), but disregards the time it will take to fully deplete these resources and the possibility that aquifers may expand across FPUs and thus contribute to a better distribution of irrigation water in space and time.

Our assumption of 40% freshwater availability is a valid threshold for maximum runoff extraction at global scale, but may be high or low in specific river basins, for example, where irrigation infrastructure is prohibitively expensive, those in which periods of inundation are needed for the functioning of riparian ecosystems, or those where flushing of solid waste and sediment is essential for stream flow, water quality control, or denitrification. Regions with irrigation constraints may need to explore options to increase irrigation project efficiency, which can easily double the irrigation water supply (34). This need for improved irrigation efficiencies is also generally true if irrigation is to play a role in reducing detrimental climate change impacts on agricultural productivity (Fig. 5).

The effectiveness of CO_2 fertilization is a source of major uncertainty, with respect to not only crop productivity [Deryng et al. (31) in this issue on PNAS] but also IWD (10). It may be the only mechanism that can alleviate some climate change impacts on agricultural irrigation water consumption and crop yields (Fig. 5), which otherwise decline rapidly with increasing temperatures. There are additional socioeconomic issues associated with irrigation consumption that we do not address here. Whereas it may be technically possible to increase yields by a relatively small 5–10% per year in the eastern United States and across much of Europe through irrigation, for example, it may not be economical to do so in practice due to the cost of irrigation relative to the potential increase in production. Additional socioeconomic issues such as transboundary disputes on appropriate river discharge rates will continue to be a problem in many arid regions.

Conclusions

We demonstrate in a unique and broad model intercomparison across two different but closely interrelated impact sectors that a conversion of currently rainfed cropland to irrigated cropland (to the extent possible given actually available water resources) would be insufficient to compensate detrimental climate change

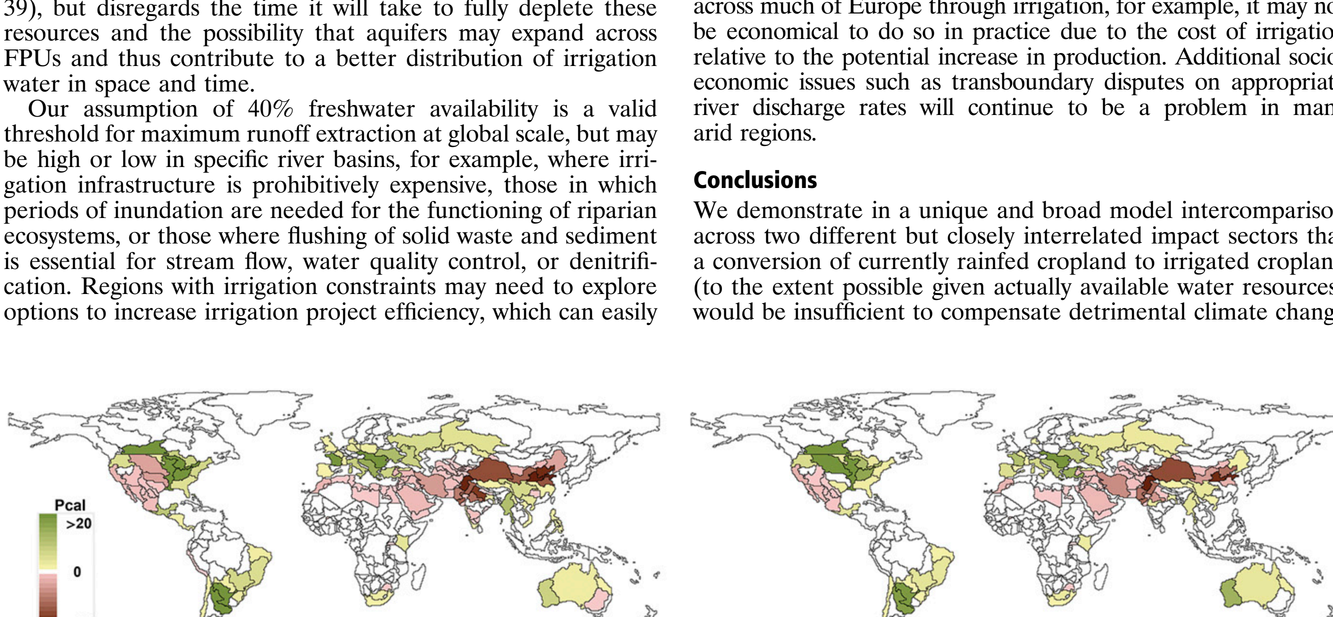

Fig. 4. Potential change in total production of maize, soybean, wheat, and rice at end-of-century given maximal use of available water for increased/decreased irrigation use on what are currently rainfed/irrigated areas in total calories. (*Left*) Median of 156 GCM × GHM × GGCM combinations for scenarios constructed using GHM estimates of present-day irrigation demand. (*Right*) Median of 202 GCM × GHM × GGCM combinations for scenarios constructed using GGCM estimates of present-day irrigation demand.

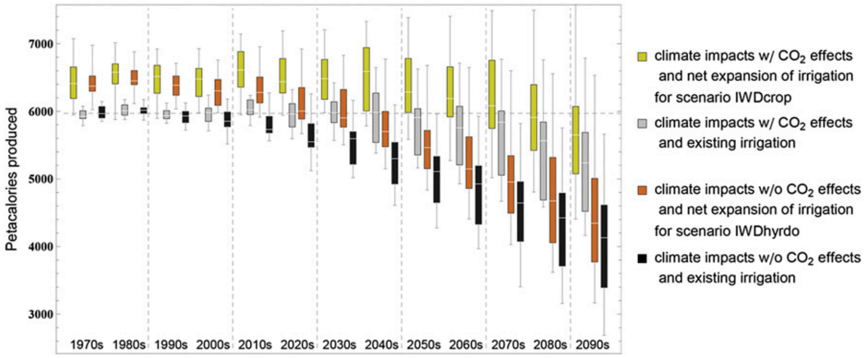

Fig. 5. Comparison of the total annual global calories of maize, soybean, wheat, and rice for RCP 8.5 as projected by four sets of ensemble simulations. The first two sets assume no change in irrigated areas and consist of (*i*) 30 GCM × GGCM combinations with CO_2 effects and (*ii*) 22 GCM × GGCM combinations without CO_2 effects. The second two sets consist of (*iii*) 202 GCM × GHM × GGCM combinations with CO_2 effects and a global net expansion in irrigated areas according to the IWDcrop scenario, and (*iv*) 156 GCM × GHM × GGCM combinations without CO_2 effects and a global net expansion in irrigated areas according to the IWDhydro scenario.

impacts on current agricultural land. The main drivers of this effect are projected water limitations, mainly in regions with already large fractions of irrigated agriculture, and the detrimental effects of climate change on agricultural productivity. Both those regions that are projected to suffer water limitations and those that are projected to have potential to expand irrigation could benefit from reduced water losses in conveyance and application and also from better-tuned deficit irrigation to increase overall efficiency of irrigation water use. Depending on local conditions, increases in irrigation capacity and efficiency need to be complemented by efforts to increase water use efficiency and soil conservation in rainfed systems as well, which have a demonstrated capacity to boost crop yields without further exploiting freshwater resources in rivers and aquifers (40). Further efforts to increase productivity, including other means of intensification, water saving, and land-use/land-cover change are needed to close what is projected to be a growing gap between agricultural production on current cropland under climate change and increasing demand for agricultural commodities. Effective climate mitigation must also be among the foremost measures to maintain current productivity on rainfed and irrigated land.

Uncertainties in these projections that result from our crop and hydrology models are generally somewhat higher than those that result from the five climate models that we use to drive the impact models, but the ensemble overwhelmingly supports the general conclusions. Nevertheless, impact model differences need to be better understood especially with respect to their implications for manageability of water consumption and climate change impacts.

Materials and Methods

Throughout this analysis we used downscaled, bias-corrected outputs of five GCMs from the Fifth Coupled Model Intercomparison Project [CMIP5 (41)] summarized in the *SI Appendix*, Table S2. See Hempel et al. (42) for a discussion of the bias correction approach and Hagemann et al. (43) for a discussion of the impact of using bias corrected climate model output with GHMs. For simplicity we have considered only a single representative concentration pathway [RCP 8.5 (44)] throughout this analysis.

Water Availability. To calculate water availability (blue water potentially available for irrigation) for each of 309 FPUs, we use simulated runoff provided by each GHM at grid cell level. Thus, we only consider the renewable surface water, including subsurface runoff, assuming that no fossil groundwater is available. Note that due to lateral water transport along river networks, the blue water available within an FPU may stem from adjacent FPUs that are (partly) located in the same river basin. To take this factor into account, we distributed the overall runoff within river basins according to the average discharge rates (taken from the GHMs) and then aggregated for each FPU. In addition, we assumed that only up to 40% of the thus computed renewable water is available for human use, so as to account for environmental flow requirements in rivers and to stay below thresholds of water stress detrimental to ecosystems and human society [following Gerten et al. (45)]. We assumed that a part of the renewable water resource is consumed for nonagricultural purposes before, and irrespective of, the crop IWD. Note that instead of water withdrawal we consider water consumption, i.e., the amount of water that is actually lost from the system (whereas a part of the withdrawn water remains available for downstream users due to return flows to the rivers).

WaterGAP Estimates for Domestic and Industrial Water Use. We estimated spatially distributed present and future total water withdrawals for the four nonagricultural water use sectors: domestic, manufacturing, thermoelectricity, and livestock (37). We calculated country-wide estimates of future water use (water withdrawals and consumption) in the manufacturing and domestic sectors based on socioeconomic projections following the Shared Socio-Economic Pathway 2 middle-of-the-road scenario [SSP Database (46)] (47). To determine the amount of cooling water withdrawn for thermal electricity production, we multiplied for each power station its annual thermal electricity production by its water use intensity. Future projections of thermal electricity production were calculated with the Integrated Model to Assess the Global Environment (IMAGE) model (48). Input data on location, type, and size of power stations were based on the World Electric Power Plants Data Set (49). The water use intensity is impacted by the cooling system and the source of fuel of the power station. We distinguished four types of fuels (biomass and waste; nuclear; natural gas; and oil, coal, and petroleum) with three types of cooling systems [tower cooling, once-through cooling, and ponds (total nonagricultural water withdrawals summarized in *SI Appendix*, Fig. S2)] (50).

Maximum Agricultural Potential with Irrigation. To understand the implications of changed irrigation water use for the balance of water consumption and freshwater supply, we translate estimates of PIrrUse into the total PIrrWW based on the current irrigation project efficiencies from Rost et al. (34), in which countries are estimated to have a total irrigation efficiency (conveyance plus application) ranging from 0.294 to 0.855. We define maximum agricultural potential with irrigation in an FPU to be total production assuming that all water available for irrigation is used. For this analysis we consider 16 of the most important global crop types (including grass/pasture). Because of the extreme diversity of global agriculture, however, it is not possible to include all crops that are important for irrigation in all regions. In total, the 16 crops simulated by at least one GGCM account for 85.5% of the global irrigated areas recorded in MIRCA2000 (monthly irrigated and rainfed crop areas around the year 2000) (*SI Appendix*, Fig. S1 and Table S5). We consider expansion/contraction only in those agriculture lands used for the four main staple food and feed crops in the world: maize, wheat, soybean, and rice. For all other crops, we assumed that irrigated areas remain fixed at present-day levels. If an FPU is deemed irrigation constrained in a given year (for a given element in the GCM × GHM × GGCM ensemble) we assume that a fraction of the cropland that is equipped for irrigation must go without, producing yields according to the rainfed estimate for that area instead. Thus, to reduce the irrigation demand by an amount T cubic meters in an FPU where the average water demand for irrigated areas in the given year is D cubic meters per hectare, the amount of land irrigated must be reduced by (T/D) hectare. Given an average irrigated yield of Y_I tonnes per hectare in the given FPU and an average rainfed yield of Y_R tonnes per hectare, the loss of production is thus $(T/D)(Y_I/Y_R)$. We do not address here the possibility of imperfect or deficit irrigation (i.e., that all areas equipped for irrigation receive something less than 100% of the demanded water, rather than some receiving zero). If more than a single crop is irrigated in a given FPU, we assume that the same economic and cultural considerations that affect the present-day distribution of irrigation will control how changes in irrigated area are distributed; i.e., the fraction of area irrigated for each crop will remain fixed at historical levels. If, on the other hand, an FPU is deemed to have some irrigation adaptation potential, then we define the agricultural potential with irrigation to be the total production in that FPU with some fraction of the rainfed areas converted for irrigation. Here again we assume that increased irrigation water is distributed evenly according to the distribution of present-day areas equipped for irrigation. We have not allowed for any land-cover change (e.g., crop switching or an increase in the total harvested area for a given crop in a region) in this analysis.

ACKNOWLEDGMENTS. We acknowledge the World Climate Research Programme's Working Group on Coupled Modeling, which is responsible for CMIP, and we thank the climate modeling groups (*SI Appendix*, Table S2) for making their outputs available. For CMIP, the US Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support in partnership with the Global Organization for Earth System Science Portals. The ISI-MIP Fast Track project was funded by the German Federal Ministry of Education and Research (BMBF) with Project Funding Reference 01LS1201A. This work was also supported in part by the National Science Foundation (NSF) under Grants SBE-0951576 and GEO-1215910. The research leading to these results has received funding from the European Union's Seventh Framework Programme FP7/2007-2013 under Grant Agreement 266992. Computing was provided by a number of sources, including the University of Chicago Computing Cooperative, the University of Chicago Research Computing Center, and through the National Institutes of Health with resources provided by the Computation Institute and the Biological Sciences Division of the University of Chicago and Argonne National Laboratory, under Grant S10 RR029030-01. Part of the computing was facilitated using the Swift parallel scripting language, supported in part by NSF Grant OCI-1148443. S.N.G. was supported by a Science, Technology, and Society Priority Group grant from the University of Nottingham. Y.M. was supported by the Environment Research and Technology Development Fund (S-10) of the Ministry of the Environment, Japan. Q.T. is supported by the 973 Program of China (2012CB955403). S.O. acknowledges support by the Formas Strong Research Environment "Land Use Today and Tomorrow." This work has been conducted under the framework of ISI-MIP and in partnership with the AgMIP community. K.F. was supported by Federal Ministry for the Environment Grant 11 II 093 Global A SIDS and LDCs.

1. United Nations (2008) United Nations, World Population Prospects: The 2008 Revision Population Database (United Nations Publications, New York) No. 200.
2. Edgerton MD (2009) Increasing crop productivity to meet global needs for feed, food, and fuel. *Plant Physiol* 149(1):7–13.
3. Pimentel D, Pimentel M (2003) Sustainability of meat-based and plant-based diets and the environment. *Am J Clin Nutr* 78(3 Suppl):660S–663S.
4. US Department of Agriculture (2009) Summary Report: 2007 National Resources Inventory (Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa).
5. de Fraiture C (2007) Integrated water and food analysis at the global and basin level. An application of WATERSIM. *Water Resour Manage* 21(1):185–198.
6. Mueller ND, et al. (2012) Closing yield gaps through nutrient and water management. *Nature* 490(7419):254–257.
7. Yoshikawa S, Cho J, Hanasaki N, Khajuria A, Kanae S (2013) An assessment of global net irrigation water requirements from various water supply sources to sustain irrigation: rivers and reservoirs (1960–2000 and 2050). *Hydrol Earth Syst Sci Discuss* 10(1):1251–1288.
8. Haddeland I, et al. (2014) Global water resources affected by human interventions and climate change. *Proc Natl Acad Sci USA* 111:3251–3256.
9. Fischer G, Tubiello F, van Velthuizen H, Wiberg D (2007) Climate change impacts on irrigation water requirements: Effects of mitigation, 1990–2080. *Technol Forecast Soc Change* 74(7):1083–1107.
10. Konzmann M, Gerten D, Heinke J (2013) Climate impacts on global irrigation requirements under 19 GCMs, simulated with a vegetation and hydrology model. *Hydrol Sci J* 58(1):88–105.
11. Bondeau A, et al. (2007) Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Glob Change Biol* 13(3):679–706.
12. Gosling S, Arnell N (2011) Simulating current global river runoff with a global hydrological model: Model revisions, validation, and sensitivity analysis. *Hydrol Processes* 25(7):1129–1145.
13. Vörösmarty C, Peterson B, Lammers R, Shiklomanov I, Shiklomanov A (1998) A Regional, Electronic Hydrometeorological Data Network for the Pan-Arctic Region (University of New Hampshire, Durham, NH). Available at www.r-arcticnet.sr.unh.edu. Accessed October 1, 2013.
14. Stacke T, Hagemann S (2012) Development and evaluation of a global dynamical wetlands extent scheme. *Hydrol Earth Syst Sci* 16(8):2915–2933.
15. Wada Y, et al. (2010) Global depletion of groundwater resources. *Geophys Res Lett* 37(20):L20402.
16. Liang X, Lettenmaier D, Wood E, Burges S (1994) A simple hydrologically based model of land surface water and energy fluxes for general circulation models. *J Geophys Res* 99:14415–14428.
17. Hanasaki N, et al. (2008) An integrated model for the assessment of global water resources—Part 1: Model description and input meteorological forcing. *Hydrol Earth Syst Sci* 12(4):1007–1025.
18. Döll P, Kaspar F, Lehner B (2003) A global hydrological model for deriving water availability indicators: Model tuning and validation. *J Hydrol (Amst)* 270(1):105–134.
19. Pokhrel Y, et al. (2012) Incorporating anthropogenic water regulation modules into a land surface model. *J Hydrometeorol* 13(1):255–269.
20. Tang Q, Oki T, Kanae S, Hu H (2007) The influence of precipitation variability and partial irrigation within grid cells on a hydrological simulation. *J Hydrometeorol* 8(3):499–512.
21. Liu J, Zehnder A, Yang H (2009) Global consumptive water use for crop production: The importance of green water and virtual water. *Water Resour Res* 45(5):W05428.
22. Jones J, et al. (2003) The DSSAT cropping system model. *Eur J Agron* 18(3):235–265.
23. Elliott J, et al. (2013) The parallel system for integrating impact models and sectors (pSIMS). *Proceedings of the Conference on Extreme Science and Engineering Discovery Environment: Gateway to Discovery (XSEDE '13)*. (Association for Computing Machinery) 21:1–8.
24. Deryng D, Sacks W, Barford C, Ramankutty N (2011) Simulating the effects of climate and agricultural management practices on global crop yield. *Global Biogeochem Cycles* 25(2):GB2006.
25. Bouwman A, Kram T, Klein Goldewijk K (2006) *Integrated Modelling of Global Environmental Change. An Overview of IMAGE 2.4* (Planbureau voor de Leefomgeving, Bilthoven, The Netherlands).
26. Izaurralde R, Williams J, McGill W, Rosenberg N, Jakas M (2006) Simulating soil C dynamics with EPIC: Model description and testing against long-term data. *Ecol Modell* 192(3):362–384.
27. Rosenzweig C, et al. (2013) The agricultural model intercomparison and improvement project (AgMIP): Protocols and pilot studies. *Agric For Meteorol* 170:166–182.
28. Schewe J, et al. (2014) Multimodel assessment of water scarcity under climate change. *Proc Natl Acad Sci USA* 111:3245–3250.
29. Rosenzweig C, et al. (2014) Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proc Natl Acad Sci USA* 111:3268–3273.
30. Portmann F, Siebert S, Döll P (2010) MIRCA2000—Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling. *Global Biogeochem Cycles* 24(1):GB1011.
31. Waha K, van Bussel L, Müller C, Bondeau A (2012) Climate-driven simulation of global crop sowing dates. *Glob Ecol Biogeogr* 21(2):247–259.
32. Cai X, Rosegrant M (2002) Global water demand and supply projections. *Water Int* 27(2):159–169.
33. Kummu M, Ward P, de Moel H, Varis O (2010) Is physical water scarcity a new phenomenon? Global assessment of water shortage over the last two millennia. *Environ Res Lett* 5(3):034006.
34. Rost S, et al. (2008) Agricultural green and blue water consumption and its influence on the global water system. *Water Resour Res* 44(9):W09405.
35. Rijsberman FR (2006) Water scarcity: Fact or fiction? *Agric Water Manage* 80 (Issue 1-3):5–22.
36. Wichelns D (2010) Virtual water: A helpful perspective, but not a sufficient policy criterion. *Water Resour Manage* 24(10):2203–2219.
37. Flörke M, et al. (2013) Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study. *Glob Environ Change* 23(1):144–156.
38. Klocke N, Currie R, Tomsicek D, Koehn J (2012) Sorghum yield response to deficit irrigation. *Trans ASABE* 55(3):947–955.
39. Rodell M, Velicogna I, Famiglietti JS (2009) Satellite-based estimates of groundwater depletion in India. *Nature* 460(7258):999–1002.
40. Rost S, et al. (2009) Global potential to increase crop production through water management in rainfed agriculture. *Environ Res Lett* 4(4):044002.
41. Taylor K, Stouffer R, Meehl G (2012) An overview of CMIP5 and the experiment design. *Bull Am Meteorol Soc* 93(4):485–498.
42. Hempel S, Frieler K, Warszawski L, Schewe J, Piontek F (2013) A trend-preserving bias correction—the ISI-MIP approach. *Earth Syst. Dynam. Discuss.* 4(1):49–92.
43. Hagemann S, et al. (2011) Impact of a statistical bias correction on the projected hydrological changes obtained from three GCMs and two hydrology models. *J Hydrometeorol* 12(4):556–578.
44. Moss RH, et al. (2010) The next generation of scenarios for climate change research and assessment. *Nature* 463(7282):747–756.
45. Gerten D, et al. (2011) Global water availability and requirements for future food production. *J Hydrometeorol* 12(5):885–899.
46. Shared Socio-Economic Pathway (2012) SSP Database. [International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria]. Available at https://secure.iiasa.ac.at/web-apps/ene/SspDb. Accessed January 12, 2013.
47. van Vuuren D, et al. (2012) A proposal for a new scenario framework to support research and assessment in different climate research communities. *Glob Environ Change* 22(1):21–35.
48. Van Vuuren D, et al. (2011) The representative concentration pathways: An overview. *Clim Change* 109(1):5–31.
49. Utility Data Institute (2004) World Electric Power Plants Database. (Platts Energy InfoStore, Platts McGraw Hill Financial, New York). Available at www.platts.com. Accessed November 15, 2012.
50. Flörke M, Bärlund I, Kynast E (2012) Will climate change affect the electricity production sector? A European study. *Journal of Water and Climate Change* 3:(1)44–54.